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NONDESTRUCTIVE REGIMES OF LASER PULSE ANNEALING OF GLASS AND CERAMIC PLATES

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In the context of the uncoupled quasistatic thermoelasticity problem, an analytical relation has been obtained, which is the criterion for thermal resistance of nonmetallic materials subjected to laser pulse annealing. The use of this relation make it possible to identify nondestructive laser treatment regimes and calculate the required thermal resistance of materials, both existent and newly developed. The adequacy of the mathematical model has been experimentally verified.

Along with traditional high-temperature annealing of glass, ceramic, and semiconductor plates, another currently used method involves treating the plate surface by laser pulse radiation [1 – 4]. The fast heating of the plate by laser radiation and its slow cooling relax residual stresses formed in the surface layer under grinding and polishing [4]. However, the treated material may be partly transparent for the radiation. As the plate is heated, certain treatment regimes may arise where thermoelastic stresses will determine the process. To prevent the bending of the plate, it is usually freely fixed along its contour.

In order to determine nondestructive treatment regimes, let us analyze an uncoupled quasistatic thermoelasticity problem for a plate freely fixed along its contour. We will assume the thermophysical and mechanical properties of the plate to be temperature-independent and the plate to be heat-resistant if it is not destroyed by thermoelastic stresses while its surface in being heated to the melting point. Let us restrict ourselves to the effect of laser radiation above lasting over 10^{-5} sec (for such time values we can consider the quasistatic thermoelasticity problem [5]) and the absorption index of the plate material over 0.1 cm^{-1}, when the effects of destroying transparent optical materials (destruction on absorbing inclusions, avalanche ionizing, etc.) can be neglected.

Thermoelastic stresses are formed in a plate freely fixed along its contour under the effect of a temperature field that varies only across the plate thickness [5, 6].

If the following condition is satisfied

$$\chi\sqrt{\alpha\tau_p} \ll 1, \tag{1}$$

then the temperature field in the plate by the end of a laser pulse effect is described by the following equation [7]:

$$T(z) = T_0 + \frac{(1-R)\chi W e^{-\chi z}}{c\rho}, \tag{2}$$

where χ is the absorption index of the plate material for the laser radiation wavelength; α is the temperature conductivity of the plate material; τ_p is the laser pulse duration; T_0 is the initial temperature of the plate; R is the reflection coefficient of the plate; c and ρ are the specific heat capacity and the density of the plate material, respectively; z is the coordinate counted from the radiated surface into the depth of the plate; $W = \int_0^{\tau_p} q(t)\,dt$ is the laser radiation energy density ($q(t)$ is the laser radiation power density).

Condition (1) for most vitreous and ceramic materials is satisfied at $\tau_p < 0.1$ sec.

Thermoelastic stresses in the plate are calculated based on the relation

$$\sigma_x(z) = \sigma_y(z) = \frac{E\alpha_T(1-R)\chi W}{(1-\nu)c\rho}\left(\frac{1-e^{-\chi h}}{\chi h} - e^{-\chi z}\right), \tag{3}$$

where E is Young's modulus; α_T is the CLTE; ν is the Poisson coefficient.

Analysis of Eq. (3) shows that the maximum tensile stresses arise at the section $z = h$ where the temperature is minimal. From expression (3) we obtain a formula to calcu-

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late the energy density that produces the plate destruction by thermoelastic stresses:

$$W_T = \frac{\sigma_{st}(1-\nu)c\rho}{E\alpha_T(1-R)\chi\left(\dfrac{1-e^{-\chi h}}{\chi h} - e^{-\chi h}\right)}, \tag{4}$$

where σ_{st} is the tensile strength of the material.

The energy density required to reach the phase transformation temperature on the radiated surface T_f is calculated from the following equation:

$$W_f = \frac{(T_f - T_0)c\rho}{(1-R)\chi}. \tag{5}$$

After transforming expressions (4) and (5) and specifying the condition $W_T/W_f > 1$ we obtain the heat resistance criterion K_{hr} for a plate freely fixed along its contour that is subjected to pulse heating from a volumetric source:

$$K_{tr} = \frac{\sigma_{st}(1-\nu)}{E\alpha_T(T_f - T_0)} \geq \frac{1-e^{-\chi h} - \chi h e^{-\chi h}}{\chi h}. \tag{6}$$

The left-hand side of inequality (6) is a dimensionless constant characterizing the ratio of the strength of the plate material to the maximally possible thermoelastic stresses in it. The right-hand side is a function of the dimensionless parameter χh. If inequality (6) is satisfied, the surface of the plate is heated to the phase transformation temperature without being destroyed by thermoelastic stresses. Otherwise the plate will be destroyed by thermoelastic stresses at the energy density level that is lower than the energy required to heat the plate surface to the phase transformation temperature.

The studies of the function $f(\chi h)$ extremum indicate that graphically this function constitutes a convex curve with a maximum equal to 0.3 at $\chi h \approx 1.79$ (Fig. 1). We can see that there is a variation range of the parameter χh inside which the plate is destroyed by thermoelastic stresses under an energy density lower than the melting point of the radiated surface.

Properties of some nonmetallic materials

Material	$\dfrac{\sigma_{st}(1-\nu)}{E\alpha_T(T_f - T_0)}$
Optical glasses:	
clear:	
LK3	0.084
K8	0.070
TF1	0.065
TK12	0.063
TK16	0.067
tinted:	
ZhZS12	0.080
SZS5	0.068
NS8	0.072
Optical ceramics:	
KO3	0.065
KO4	0.012
KO6	1.130
Quartz glass	0.830

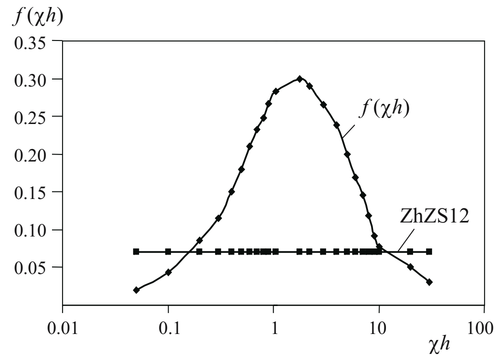

Fig. 1. Graphic solution of inequality (6) for a plate made of tinted optical glass ZhZS12.

The initial data for the calculation of the constant characterizing the properties of materials were taken from GOST 9411–90 and also from [8 – 10].

It can be seen that most nonmetal materials (except for quartz glass and ceramic KO6) have a particular variation range of the dimensionless parameter χh in which the plate may be destroyed by thermoelastic stresses. To choose nondestructive laser treatment conditions, it is necessary to select a radiation wavelength that satisfies relation (6). The proposed model requires experimental verification of its adequacy.

To verify the adequacy of the mathematical model, we investigated the effect of the radiation from a GOS-1001 laser for wavelength 1.06 μm on freely fixed plates made of tinted optical glass ZhZS12 of thickness varying from 0.4 to 1.7 cm and diameter 2 cm. The absorption index of glass ZhSS12 for the specified wavelength is 10 cm^{-1}. The analyzed samples were fully covered by the radiation. The energy density on the samples varied from one experiment to another by varying the initial beam diameter. The following parameters were measured in the experiments:

– laser radiation energy using a TPI2-5 calorimetric transformer;

– the beam diameter in the plane of the sample;

– the time interval from the start of the treatment till the destruction of the sample by thermoelastic stresses or till the surface melting (using two DF2 photodiodes and an S8-12 oscillograph).

The measured values were used to calculate the energy density required to destroy the samples. Each experimental dot was obtained by statistical processing of ten experiments. The calculation results based on relations (5) and (6), as well as the experimental data are indicated in Fig. 2.

The initial data for the calculation were taken from GOST 9411–90, as well as from [8 – 10]. When the sample thickness was below 1.5 cm and the thermal resistance criterion was not satisfied, the sample was destroyed by thermoelastic stresses. With a plate thickness over 1.5 cm, when the thermal resistance criterion was satisfied, the surface of the sample was fused. The experimental values of energy density

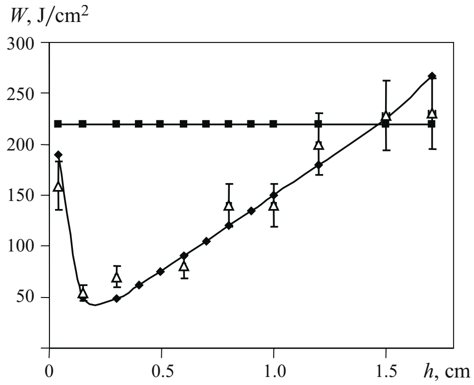

Fig. 2. Dependence of energy density causing the destruction of the plate on thickness of samples: ◆) W_T; ■) W_f; △) experimental data.

required to destroy the samples adequately agree with the calculation results.

Consequently, the adequacy of the mathematical model has been experimentally confirmed.

Thus, in the context of the uncoupled quasistatic thermoelasticity problem, an analytical relation has been obtained, which is the heat resistance criterion for nonmetal materials under laser pulse annealing. This relation makes it possible to identify nondestructive laser treatment regimes and impose requirements on heat resistance of existing and currently developed materials.

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